The potential impact of climate change on oat lodging in the UK and Republic of Ireland

Mohammadi, Mohammadreza; Finnan, John; Baker, Christopher; Sterling, Mark

DOI:
10.1155/2020/4138469

Hindawi
Advances in Meteorology
Volume 2020, Article ID 4138469, 16 pages
https://doi.org/10.1155/2020/4138469

Research Article

The Potential Impact of Climate Change on Oat Lodging in the UK and Republic of Ireland

Mohammadreza Mohammadi[1], **John Finnan**[2], **Chris Baker**[1], **and Mark Sterling**[1]

[1]*School of Engineering, University of Birmingham, Birmingham B15 2TT, UK*
[2]*Teagasc Crops Research Centre, Oak Park, Carlow R93 XE12, Ireland*

Correspondence should be addressed to Mohammadreza Mohammadi; mxm755@student.bham.ac.uk

Received 9 April 2019; Accepted 11 December 2019; Published 22 January 2020

Academic Editor: Giacomo Gerosa

This paper examines the impact that climate change may have on the lodging of oats in the Republic of Ireland and the UK. Through the consideration of a novel lodging model representing the motion of an oat plant due to the interaction of wind and rain and integrating future predictions of wind and rainfall due to climate change, appropriate conclusions have been made. In order to provide meteorological data for the lodging model, wind and rainfall inputs are analysed using 30 years' time series corresponding to peak lodging months (June and July) from 38 meteorological stations in the United Kingdom and the Irish Republic, which enables the relevant probability density functions (PDFs) to be established. Moreover, climate data for the next six decades in the British Isles produced by UK climate change projections (UKCP18) are analysed, and future wind and rainfall PDFs are obtained. It is observed that the predicted changes likely to occur during the key growing period (June to July) in the next 30 years are in keeping with variations, which can occur due to different husbandry treatments/plant varieties. In addition, the utility of a double exponential function for representing the rainfall probability has been observed with appropriate values for the constants given.

1. Introduction

Climate change, which results from the increasing trend of greenhouse gas emission, can cause major variations in meteorological parameters [1]. Global temperature, for instance, has increased by 0.74°C in the period from 1906 to 2005, and precipitation patterns have changed in some parts of the world [2]. As a large water consumer and being temperature dependent, the agriculture sector could be dramatically affected, either positively or negatively, by these changes worldwide. For example, future climate changes are supposed to have a negative effect on cereal production in western Africa, southern Europe, and central and southern Asia [3, 4], while, most parts of eastern Africa, northern Europe, northern America, and eastern and southeastern Asia will benefit from projected future meteorological conditions [4, 5]. Moreover, major parts of southern and eastern Australian farmlands will be substantially affected by climate change and will face a reduction in the crop production. Similar impact is expected for eastern parts of New Zealand, while tillage areas near major New Zealand rivers will benefit from the future climate conditions [4]. The climate change is also expected to reduce crop production in the UK and Ireland [6, 7], where southern and eastern England regions will be most affected [4].

Furthermore, it is not clear how current problems in agriculture such as lodging—the permanent displacement of crops from the root or the stem due to strong winds and high amount of rainfall—might vary in future, due to climate change effects. It is with this issue that this paper is concerned, and we will study in particular the change in lodging risk in the United Kingdom (UK) and the Republic of Ireland.

As in other parts of the world, lodging has a negative impact on the agriculture sector in the UK and Republic of Ireland, where damage to cereals and oilseed rape costs about £50 m on average each year and can reach up to more than £170 m in severe lodging years [8, 9]. The costs incurred by lodging are not only due to yield loss but also are due to the outcome of lower grain quality, increased drying costs, and longer harvest time [8, 10–12]. This substantial impact has resulted in several studies of the interaction of wind with plants in order to understand the physics of the phenomenon. The earliest notable work in this field was Wright [13] who suggested an exponential function for wind profile over plant canopies. In the following decades, several studies provided information about turbulence flow over plant canopies: Lu and Willmarth [14] discussed eddies above a plant canopy; Raupach et al. [15, 16] proposed the existence of a mixing layer above the canopy and revealed that large coherent structures dominate the dynamics of the turbulent flow, and Py et al. [17] observed the streamwise flow length scale to be proportional to canopy height. Theoretical models developed by Baker et al. [12, 18, 19] together with experimental studies on wheat [11, 20], barley [21], and sunflower [22, 23] have provided a viable method to understand the phenomenon and to predict the risk of lodging occurrence. As the main cause of the lodging is adverse weather conditions, i.e., high rainfall and strong winds [19], several studies have addressed the issue of how variations in meteorological parameters affect lodging occurrences. Easson et al. [24] reported that lodging is associated not only with strong gusts (greater than 25 km/h (7 m/s)) but also may occur in low wind speeds (16 km/h (4 m/s) or less). Meanwhile, Berry et al. [25] demonstrated that lodging can be prevented or substantially reduced using appropriate husbandry even in adverse weather conditions. In addition, Baker et al. [12, 19] and Sterling et al. [9, 26] developed probabilistic frameworks where the risk of lodging could be calculated via an understanding of the probability of crop failure in adverse weather conditions. However, it is not clear how these probabilities might vary in future. The only notable work in this field was by Martinez-Vasquez [27] who developed a lodging risk analysis building on the generalized lodging model [12] together with UKCP09 climate projector. However, due to lack of knowledge about the parameters required for the generalized lodging model for oats, the model used was not calibrated resulting in significant inaccuracies in the risk calculation. Since the publication of this work, a new version of the UK climate projector (UKCP18) has been released which not only provides updated projections but also includes both future precipitation and wind projections. In addition, recent experimental studies on oats have enabled a calibrated lodging model for oats [9].

Historical climate observations show an average increase of 0.5%–1% per ten-year rainfall in most of northern hemisphere's mid and high latitudes [28]. Nevertheless, in England and Wales, annual mean rainfall has not changed noticeably since 1766, and seasonal precipitation seems to show a decline in summer [29]. Additionally, historical data demonstrate a significant variation of rainfall in different years, whilst an overall increase in wintry precipitation can be observed [30]. In the Republic of Ireland, an increase in annual rainfall in the North and West of the country and a decline or small increase in the South and East were detected [31]. Future projections demonstrate an increase from 1°C to 1.6°C and up to 2.3°C by 2100 in mean annual temperatures in Ireland and the UK [32, 33]. Furthermore, the Republic of Ireland is expected to experience a decline in mean annual, spring, and summer precipitation amounts by midcentury, and the number of extended dry periods is expected to increase during autumn and summer [34]. Similarly, the UK summer rainfall is projected to drop by 47% by 2070, while an increase of 35% in winter precipitation is expected [33]. Climate simulators have also demonstrated a decline in energy content of the wind in all seasons except winter in both countries [35]. Due to availability of new projections, which include not only precipitation but for the first time also wind data, it is now possible to study how future precipitation and wind might affect the lodging risk in oats.

In addition to the meteorological conditions, lodging can be influenced by plant properties as affected by variety and the crop husbandry, including sowing rate, nitrogen rate, nitrogen timing, and plant growth regulator (PGR) application [25]. Moreover, other environmental conditions which affect plant growth such as topography, soil type, sunshine soil moisture, temperature, pests, and diseases can also affect the plant biological properties [8, 25, 36]. The contribution of each factor in the lodging process is hard to assess as the phenomenon is very complex. Nevertheless, Berry et al. [11] quantified the risk of lodging for wheat crops grown under different treatments and showed the lodging timing and quantity can be estimated by a calibrated lodging model. At present, there is no enough data for oats to fully quantify the impact of the full range of management impacts on lodging risk.

Based on the above, the aim of the current paper is to investigate possible effects of climate change on oat lodging in the UK and the Republic of Ireland. This study is part of a wider research to study lodging in oats, funded by Teagasc (the Republic of Ireland's Agricultural and Food Development Authority) [9, 37, 38]. The project elaborates the generalised model developed in [12] to study the oat failure risk, for different treatments/varieties as well as various meteorological conditions (i.e., wind speed and rainfall). The approach used to investigate the aerodynamic parameters of the lodging model (Section 2.2) was also applied for other ongoing projects at the University of Birmingham to study lodging in maize, oilseed rape, and rice, funded by UK Biology and Biotechnology Research Council (BBSRC) [39, 40].

Oat has been selected as the case study as the crop that has a high propensity to lodge in the UK and Ireland weather conditions [41–43]. Moreover, oat grains have been reported as a rich source of vitamins, minerals, and antioxidant, as well as having other health benefits such as reducing the cholesterol level and blood sugar [44–46]. Consequently, oat is cultivated in about 9% of crop tillage areas in Ireland [47]. Although the percentage of cultivated farmlands of oats is lower (about 1%) in the UK, it has the highest increasing rate (7.8%) in the major cereal crops (wheat, barley, oat, and oilseed rape) [48]. The methodology used in this research is given in Section 2, including an outline of historical data sources, the conceptual lodging model, and the prediction of future climate scenarios. Section 3 then outlines the development of wind and rainfall probability distributions from historical data and describes the possible future changes in these distributions due to climate change effects. Section 4 then presents an analysis of lodging risk, both for the current situation and for the predicted future climate. Finally, the implications of the results are discussed in Section 5.

2. Methodology

2.1. Historical Data. To evaluate historical meteorological conditions during the last three decades, data from 38 stations were collected from Met Éireann (the Irish Meteorological Service) [35], the United Kingdom's Meteorological Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations [49], and the Meteorological Office National Meteorological Archive (Met Office National Meteorological Archive, personal communication, 2016). These specific datasets were selected based on the availability of long-term data (1987–2016) and proximity to regions where oats are commercially grown (i.e., mainly the eastern and southern parts of Ireland and Eastern Scotland, as well as Western and Southern England [50] (RSK ADAS Ltd, personal communication, 2016)). These data were analysed to find rainfall and wind probability density functions (PDFs) which will be described further in Section 3.1.

2.2. Lodging Model and Risk Calculation. In this section, the generalized lodging model [12] is described briefly since it is a key to understanding the risk of changes in climate and is based on wind and rainfall probability density functions. In this model, the external bending moment that a plant experiences as a result of the wind is compared with the plant's stem and anchorage resistance [8]. Accordingly, two failure velocities for the stem and root failure can be defined. The stem failure criteria can be written in the format of a stem failure (lodging) velocity (U_{Ls}), i.e.,

$$U_{\mathrm{Ls}} = \left(\frac{\omega_n^2 (X/g) (\sigma \pi a^3/4) \left((1 - ((a-t)/a))^4 \right) n}{(1 + \omega_n^2 (X/g)) (0.5 \rho A_{\mathrm{CF}} X) (\cos(\alpha x/l) - \cot\alpha \sin(\alpha x/l)) (1 + I (4 g_{\mathrm{MB}}^2 + g_{\mathrm{MR}}^2 (\pi/4\theta)))^{0.5}} \right)^{0.5}, \quad (1)$$

where $\omega_n = 2\pi f_n$, f_n is the natural frequency, is the radial frequency, X is the height of the centre of mass of the canopy, g is the gravity acceleration, σ is the stem yield stress, a is the stem radius, t is the stem wall thickness, n is the number of stems per plant, ρ is the air density, A_{CF} is the plant shear area for a plant in a canopy, α is a dimensionless parameter, x is the distance up to the stem from the ground, l is the length of stem, I is the turbulence intensity, and θ is the damping ratio. Additionally, g_{MB} and g_{MR} are the gust factor of broad-banded stem moment and the gust factor of resonant stem moment, respectively [51].

Similarly, the failure root velocity known as root lodging (U_{LR}) can be defined as

$$U_{\mathrm{LR}} = \left(\frac{\gamma S d^3}{((1 + \omega_n^2 (X/g))/\omega_n^2 (x/g)) (0.5 \rho A_{\mathrm{CF}} X) (1 + 2 I g_{\mathrm{MB}})} \right)^{0.5}, \quad (2)$$

where S is the soil shear strength, d is the effective root diameter, and γ is a constant. As the stem and root lodging velocities (equations (1) and (2)) are based on a variety of crop parameters (e.g., natural frequency and drag area), different experiments were undertaken to investigate these parameters in two separate field trials—one in 2017 and one in 2018. The experimental setup designed to study the turbulent flow over plant canopies and the dynamic of plant movement of crops included two sonic anemometers (to record wind velocity above the canopy) and two video cameras to observe the crop's movement. The acquired wind and video data were later postprocessed through standard wind engineering methods to study the turbulent flow over oat canopies and to obtain required aerodynamic parameters for the model. Full details relating to these experiments can be found in [9, 37, 52]. Furthermore, additional experiments were undertaken to identify the plant-related parameters grown under different varieties/treatments and various soil conditions. These field experiments were mainly based on agronomic measurement protocols developed by Berry et al. [53].

Figure 1 illustrates graphically how equations (1) and (2) can be interpreted. In Figure 1, the vertical axis represents the daily rainfall (i), and the horizontal axis is the hourly mean wind speed (U). Various regions have been defined in Figure 1. For example, the curve (equation (3)) defines the lodging/no-lodging boundary and illustrates the relative contributions of rainfall and wind speed required for lodging to occur. The curve is given by

$$i = \left(1 - \frac{U^2}{U_{\mathrm{LR}}^2} \right) i_0, \quad (3)$$

where i is the daily rainfall and i_0 is the reference rainfall corresponding to zero wind speed. It should be noted that Figure 1 is plotted for a sample data from oats, and thus, the curve and dashed lines can be replotted for other oat sample data or other crops.

The risk of lodging can be obtained using integration of joint (wind and rain) probability density function in the region where the risk of lodging exists. Baker et al. [12] used a Rayleigh distribution for wind PDF given by

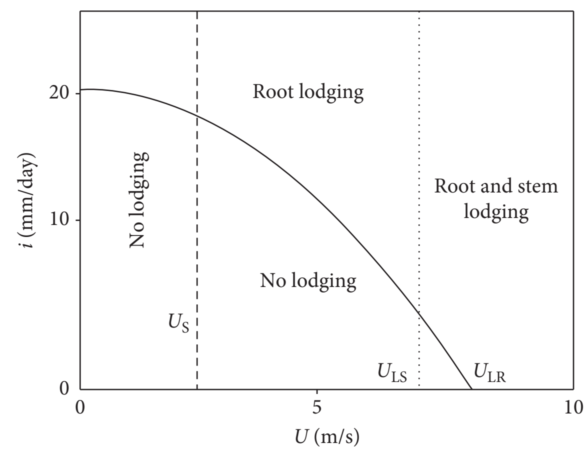


Figure 1: Lodging regions in the daily rainfall/hourly mean wind speed plane for a sample oat plant.

$$p(U) = \left(\frac{2}{\lambda}\right)\left(\frac{U}{\lambda}\right)e^{-\left(U^2/\lambda\right)}, \tag{4}$$

where $p(U)$ is the PDF for (U) and λ is a parameter used to characterize the wind climate. The Rayleigh distribution was preferred rather than the Weibull distribution since it enabled an analytical form of the lodging risk to be calculated. For the rainfall PDF, an exponential function was used:

$$p(i) = \left(\frac{1}{m}\right)e^{-(i/m)}, \tag{5}$$

where m is the mean daily rainfall and i is the daily rainfall. At the time, equation (5) was a convenient expression; however, Baker et al. [12] emphasised the necessity of additional research in order to establish a more appropriate representation for the rainfall PDFs [12, 26].

2.3. Future Scenario Projection. UKCP18 provides the most recent projections for future climate conditions in the coming decades based on a number of data sources and emission scenarios for different periods and locations [54]. Emission scenarios in UKCP18 are defined as Representative Concentration Pathways (RCPs), which determine the amount of greenhouse gases causing certain radiative forcing at the high altitude of the Earth's atmosphere by 2100, in comparison to preindustrial levels [55]. Four forcing levels are used: 2.6, 4.5, 6.0, and 8.5 W/m^2, which are defined as RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 scenarios [33]. Land projections in the UKCP18 include probabilistic, global, and regional outcomes. Probabilistic projections are designed to demonstrate the ranges of uncertainty in the outputs for a certain period, location (region), and different emission scenarios. Global/regional projections both use RCP 8.5 and illustrate 28/12 climate projections at a 60 km/12 km grid resolution, respectively [56].

3. Climate Data and Predictions

3.1. Wind and Rainfall PDFs. Figure 2 shows sample data relating to PDFs for selected stations in Ireland, England, and Scotland. In Figure 2, the horizontal axis illustrates rainfall, and the vertical axis shows the correspondent probability. These are for the months of June and July, when lodging events are known to occur. To identify an appropriate function, a curve is fitted on each station using MATLAB, and a double exponential was found to be the best representative function:

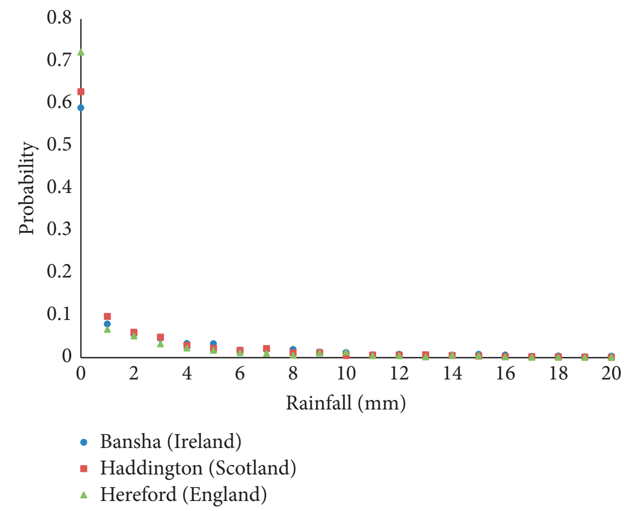


Figure 2: Rainfall probability density function for selected Irish, Scottish, and English meteorological stations in the period from 1987 to 2016 for June and July [35, 49] (Met Office National Meteorological Archive, personal communication, 2016).

$$P(i) = ae^{-bi} + ce^{-di}, \tag{6}$$

where i is the amount of daily rainfall, $P(i)$ is the probability, and a, b, c, and d are site-dependent coefficients. Despite the geographic variation of rainfall, it was found that the overall PDFs can be defined at regional scales for Ireland, Scotland, and England (Table 1). Furthermore, it was observed that, through appropriate selection of the values of a, b, c, and d, an overall curve could be obtained which represented all of the data irrespective of location to a reasonable degree of accuracy, i.e., 0.2%. It should be noted that the values of the aforementioned constants are not independent but have been chosen to ensure that they are consistent with the cumulative density function (CDF) tending to unity as the rainfall tends to infinity.

A similar analysis was undertaken for the wind speed, and it was observed that a Weibull distribution, given by

$$P(U) = \frac{k}{\lambda}\left(\frac{U}{\lambda}\right)^{k-1} e^{-(U/\lambda)^k}, \tag{7}$$

best represented the data. Here, λ and k are parameters governing the scale and shape of the distribution, respectively. Figure 3 illustrates the results of the analysis for 10 stations in Ireland and the UK together with the final curve used to represent all data ($\lambda = 4.4$, $k = 1.8$). The largest difference between the actual data and the fitted curve is ~12% and occurs in low-speed conditions, i.e., conditions when lodging risk is minimum.

Table 1: Coefficients for regional and overall representative curves for rainfall PDFs and corresponding curve difference with actual data.

	a	b	c	d	Mean-squared error
Ireland	0.60	0.75	0.02	0.01	0.002
England	0.70	0.88	0.03	0.15	0.002
Scotland	0.60	0.75	0.03	0.15	0.002
Overall	0.62	0.83	0.03	0.12	0.002

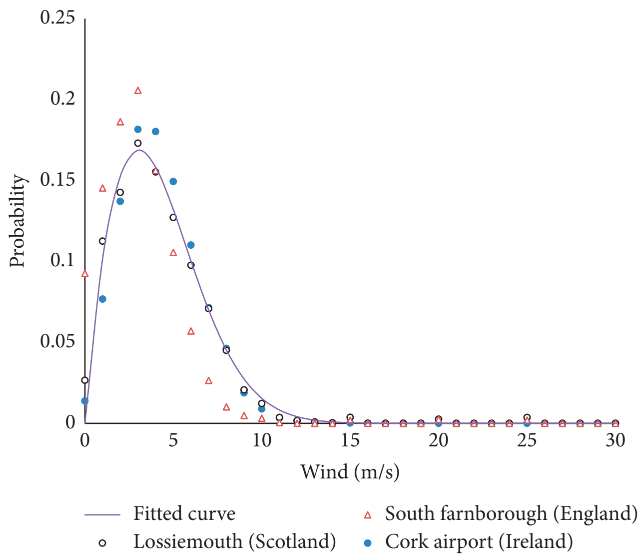


Figure 3: Wind probability density function 1987–2016 for selected Irish, Scottish, and English meteorological stations [35, 49].

3.2. Future Climate Projection. Projections of UKCP18 show warmer, wetter winters and hotter, drier summers for the UK. All the regions of the UK are predicted to face higher temperatures, and the increase is greater in summers rather than in winters. Perhaps not surprisingly, geographic and seasonal variation of precipitation is likely to continue to exist in future. This section discusses results from the UKCP18 where probabilistic, global, and regional projections are presented in Sections 3.2.1–3.2.3.

3.2.1. Probabilistic Projections (25 km Resolution). Probabilistic projections merge historical weather data with climate models and statistics at 25 km grid resolution to provide outputs for different emission scenarios and are an appropriate tool to study the effect of different RCPs on precipitation anomalies. However, the tool provides data only for UK areas and does not include projections for the Irish Republic. Figure 4 illustrates precipitation rate anomalies in June and July, respectively, in all the UK areas using the 1981–2010 baseline and geographic variations in rainfall anomalies can be clearly observed. The figure includes three panels for 10th, 50th, and 90th percentiles, and each square indicates the range of change in the area. For example, a grid showing 10% precipitation anomaly rate in 50th percentile represents 50% probability that monthly rainfall will increase by less than 10% [54]. As all RCPs show similar outcomes, only data corresponding to RCP 2.6 are presented here. The figure shows drier conditions for southern regions of England in June and July, while western regions of Scotland are projected to experience wetter climate in June.

A probabilistic projection tool was employed to analyse data at 16 stations across southern and western areas of England, as well as eastern and southern regions of Scotland (areas where oats are commercially grown). Results illustrate that for all stations, different emission scenarios have only a slight effect on precipitation rate anomaly (%), although the difference between emission scenario plots is larger in July. Figure 5 illustrates an example of a CDF for monthly rainfall changes at a sample weather station (Herford, England) for different emission scenarios. More details, regarding the anomaly ranges from 10th percentile to 90th percentile, are presented in Table 2. As illustrated in Figure 5, different RCPs result in different CDFs, which are perhaps not too surprising given the complexity of the climate model and the uncertainty associated with this particular area.

3.2.2. Global Projections (60 km Resolution). Global projections are based on 28 climate models at 60 km grid resolution including 15 simulations of the Met Office Hadley Centre model (HadGEM3-GC3.05), and 13 other outputs are adopted from the Intergovernmental Panel on Climate Change's 5th Assessment Report, CMIP5-13 [30]. Using these two series of climate models increases the range of plausible futures.

The HadGEM3-GC3.05 is a coupled atmosphere-ocean configuration, including different levels of stratosphere, atmospheric chemistry, vegetation, and ocean biology [33]. In each model's output, all plausible variants perturbed in the given climate model configuration, building a perturbed parameter ensemble (PPE) [57]. These variants can be classified as convection parameters, mountain effects, atmospheric boundary layer conditions, cloud radiation and microphysics features, and aerosol parameters which can be found in [57]. Later, PPEs were filtered to provide highest plausibility and diversity of outputs, producing 15 simulations [57].

In order to add diversity to the projections, 13 CMIP5 models (CMIP5-13) are also provided simulating global and zonal mean temperatures in the Earth's surface, global trend of sea surface temperature (SST) bias and Atlantic Meridional Overturning Circulation (AMOC), as well as climatological conditions over the North Atlantic and Europe [57]. Table 3 shows models incorporating in CMIP5-13 and associated modelling groups.

Figure 6 shows results of global projection from these 28 climate models at 60 km resolution. In addition to model designations described in Table 3, 15 PPEs from HadGEM3-GC3.05 are presented as five-digit numbers. These numbers are allocated to name selected PPEs by UKCP18 designers and do not have any significance (Met Office, personal communication, 2019). The results illustrate that in the most severe predictions, southern regions of Ireland might get 30–40% drier in June and July. However, some models

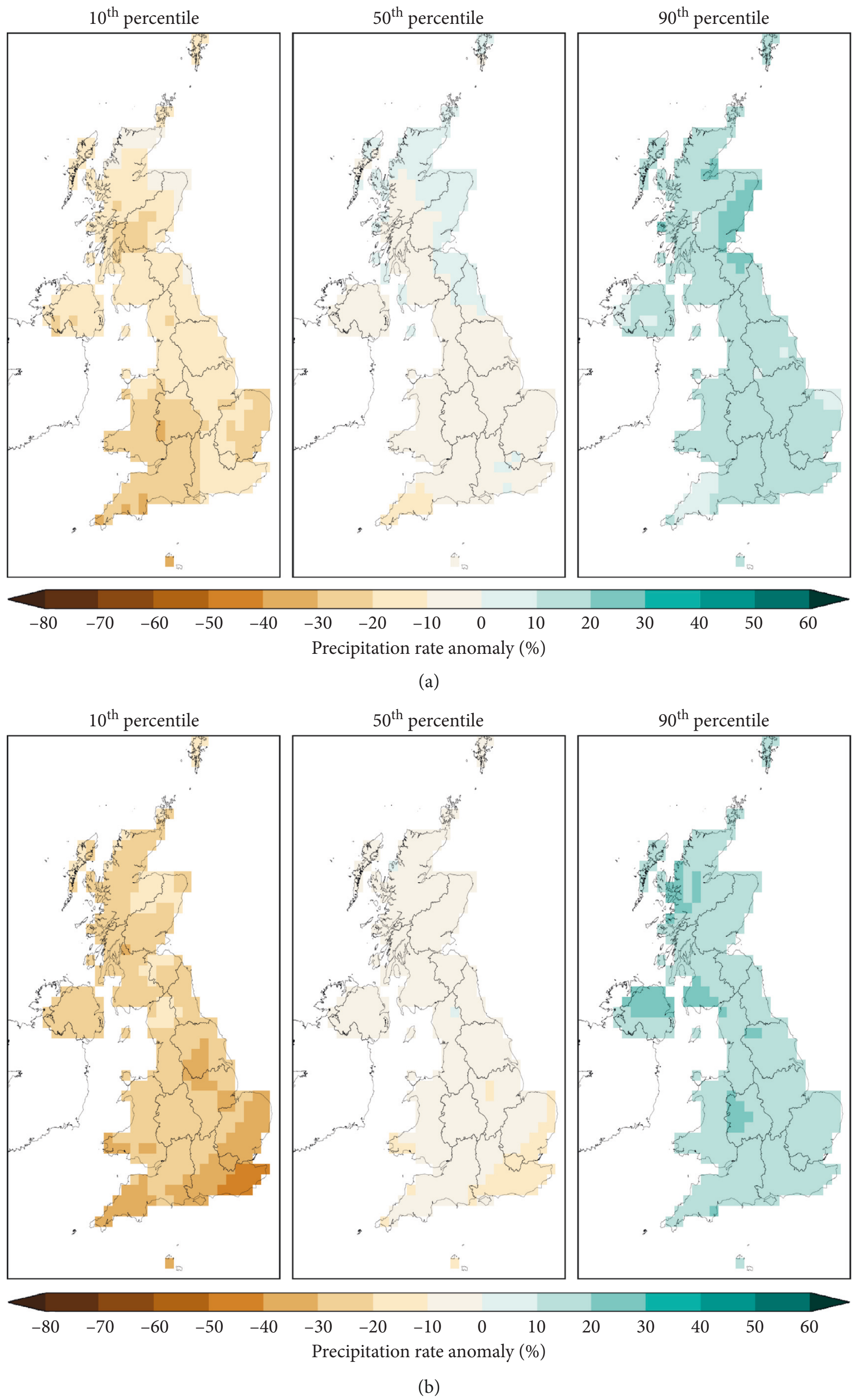


Figure 4: Monthly average precipitation rate anomaly (%) for RCP 2.6 from 2020 to 2049 using baseline 1981–2010 and scenario RCP 2.6 (a) in June and (b) in July.

predict a different trend suggesting an increase of precipitation of up to 40% increase in precipitation. In general, the majority of the models show a predicted difference of ±20% in June and July.

With respect to England, the majority of the projections suggest that June will be 10% to 30% drier, although regions in the South could experience up to 30% increase in rainfall. In July, most models show drier conditions (up to 60%

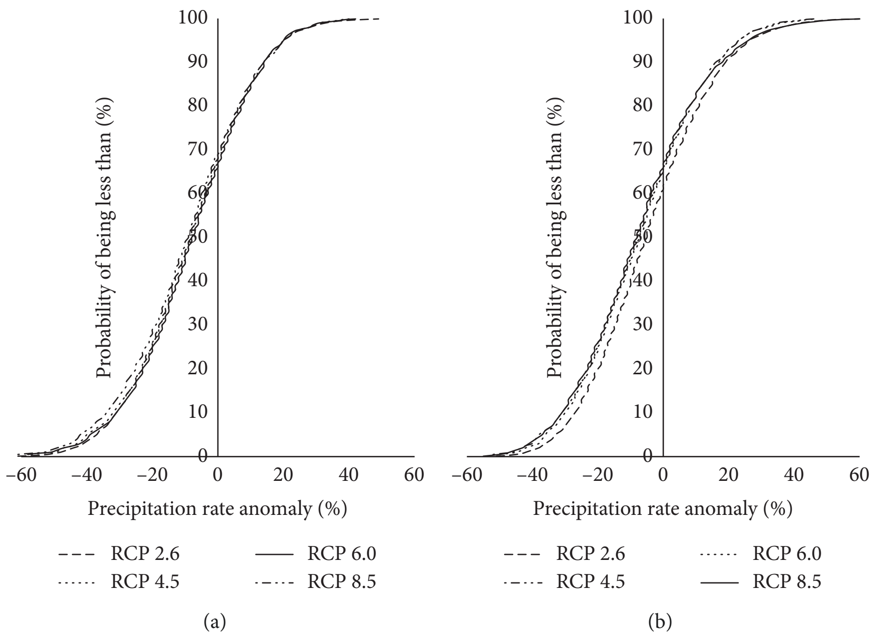


Figure 5: Cumulative distribution function for precipitation rate anomaly in Herford, England, for RCPs used in the UKCP18 in (a) June and (b) July.

especially in southern parts) whilst the extreme cases suggest a 40% increase in rainfall. Finally, precipitation in Scotland is expected to experience ±30% and ±20% anomalies in June and July, respectively.

3.2.3. Regional Projections (12 km Resolution). Regional projections are based on HadGEM3-GC3.05 and use 12 PPEs in a downscaled area in comparison to the global projection which enables the effect of physiographic features including mountains, coasts, urban areas, lakes, and rivers being considered. Figure 7 illustrates precipitation maps of anomalies for regional projections for the RCP 8.5 scenario. These outputs are generated by 12 projections from the Met Office Hadley Centre model at 12 km scale resolution. In general, most models show the UK and Ireland will tend to experience drier condition in June and July with variations corresponding to Ireland between ±20% and up to 50% reduction in the monthly rainfall in southern regions. Furthermore, the majority of the models implies southern and western regions of England will become drier in June and July while variation of projections in eastern parts is from 40% drier to 50% wetter condition. Finally, Scottish areas are projected to experience mainly ±30% anomaly in precipitation.

Figure 8 shows the monthly average wind speed anomaly at 10m above the ground from 2020 to 2049 for June and July. This figure illustrates the wind speed change in both England and Ireland is ±1 m/s, i.e., a relatively small change. A slight increase is observed in Scotland, but again, this predicted increase is small and from a lodging perspective is unlikely to be significant.

3.2.4. Summary of Projections. UKCP18 outputs produced by different models are summarized in Table 2, where results are presented for 2020–2049 and 2050–2079 periods. Probabilistic projections demonstrate anomaly ranges from the 10^{th} percentile to 90^{th} percentile, while regional and global variations represent the largest anomaly projected. For the same periods (2020–2049 and 2050–2079), wind predictions show ±1 m/s change in all studied areas. The Republic of Ireland is mainly projected to face a reduction in average wind speed except in a few areas on the northern and southern coasts. Results for the UK appear to be spatially variable.

4. Lodging Risk Assessment

4.1. Lodging Risk in Current Climate Conditions. To investigate the risk of lodging in autumn-sown oats in current conditions, a database of 1,000 synthetic plants was generated based on mean values and standard deviations of plant parameters including panicle area, stem radius, stem wall thickness, centre of gravity, effective root diameter, anchorage depth of the rooting system, and the number of stems per plant provided in Table 4 (in keeping with the approach of [11]), i.e., for each synthetic sample, the plant parameters were randomly generated assuming a corresponding normal distribution (see [11]). Experience has shown that 1,000 samples are significant to ensure that the results are statistically independent, and thus, relevant conclusions can be drawn. In order to provide the input to the database, plant data (mean and standard deviations) were obtained from field experiments undertaken in 2016-2017 at Knockbeg, County Laois, the Republic of Ireland (52.86°N, 6.94°E, 54 MSL). Plants were raised from two varieties (an oat variety susceptible to lodging (Barra) and an oat variety with moderate resistance to lodging (Husky)) grown under different combinations of agronomic treatments designed to create a range of lodging pressures. Thus,

Table 2: Monthly average precipitation rate anomaly (%) using baseline 1981–2010 in June and July.

Month	Region	Projection	2020–2049				2050–2079			
			RCP 2.6	RCP 4.5	RCP 6	RCP 8.5	RCP 2.6	RCP 4.5	RCP 6	RCP 8.5
June	South England	Probabilistic	−26% to +17%	−24% to +19%	−24% to +19%	−27% to +19%	−37% to +3%	−42% to 2%	−43% to +2%	−50% to +4%
		Regional				−50% to +50%				−70% to +20%
		Global				−40% to +40%				−70% to +20%
	West England	Probabilistic	−31% to +22%	−30% to +22%	−29% to +22%	−32% to +21%	−38% to +4%	−43% to +3%	−44% to +3%	−51% to +4%
		Regional				−50% to +30%				−70% to +10%
		Global				−40% to +40%				−70% to +20%
	Scotland	Probabilistic	−18% to +22%	−17% to +22%	−17% to +23%	−17% to +22%	−25% to +14%	−27% to +14%	−27% to +14%	−29% to +14%
		Regional				−30% to +60%				−40% to +30%
		Global				−40% to +40%				−50% to +30%
	Ireland	Regional				−50% to +20%				−70% to 0%
		Global				−40% to +30%				−60% to +20%
July	South England	Probabilistic	−43% to +16%	−44% to +16%	−44% to +17%	−47% to +14%	−44% to +12%	−49% to +9%	−49% to 10%	−56% to +7%
		Regional				−40% to +50%				−60% to +10%
		Global				−50% to +50%				−70% to +30%
	West England	Probabilistic	−27% to +19%	−29% to +19%	−28% to +19%	−31% to +18%	−37% to +9%	−41% to +8%	−40% to +8%	−47% to +5%
		Regional				−40% to +20%				−60% to +10%
		Global				−30% to +50%				−60% to +30%
	Scotland	Probabilistic	−28% to +22%	−28% to +22%	−28% to +22%	−30% to +21%	−38% to +15%	−40% to +17%	−40% to +17%	−47% to +19%
		Regional				−40% to +30%				−50% to +10%
		Global				−30% to +40%				−50% to +20%
	Ireland	Regional				−50% to +30%				−60% to −10%
		Global				−40% to +40%				−60% to +40%

Table 3: The CMIP5-13 models used in UKCP18 under the RCP 8.5 scenario [57].

Model designation	Modelling group
CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici
BCC-CSM1	Beijing Climate Centre, China Meteorological Administration
CanESM2	Canadian Centre for Climate Modelling and Analysis
ACCESS1-3	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
CESM1-BGC	Community Earth System Model Contributors
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
EC-EARTH	EC-EARTH consortium
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory
HadGEM2-ES	Met Office Hadley Centre
IPSL-CM5A-MR	Institute Pierre-Simon Laplace
MPI-ESM-MR	Max-Planck-Institut für Meteorologie
MRI-CGCM3	Meteorological Research Institute
CCSM4	National Centre for Atmospheric Research

four different synthetic databases were generated corresponding to variety/seed rate combinations outlined in Table 5, as well as a database is generated based on Table 4 associated with natural variations of oat parameters.

As illustrated in equations (1) and (2), in addition to the agronomic parameters (stem strength etc.), the lodging model also relies on soil and aerodynamic parameters, including drag coefficient, air density, natural frequency, damping ratio, and turbulence intensity, provided in Table 4. The aerodynamic parameters were evaluated using standard wind engineering methods [9], while soil shear strength was measured in the studied site. Table 5 shows the 10^{th}–90^{th} percentile range as well as the 50^{th} percentile lodging risks in the generated synthetic databases. A relatively large spread of risk in each sample variety/seed rate can be observed and illustrates that different husbandry treatments/varieties can result in considerable differences in failure probabilities—this is an important result which will be discussed in the following sections.

The risk of lodging might also change in different sites due to differences in meteorological conditions, especially wind PDF (Figure 3). Accordingly, the lodging risk was assessed for average agronomic values (Table 4) for 9 studied stations in England, Scotland, and Ireland (3 stations in each region). The risk assessment was undertaken using the representative (overall) rainfall PDF (Table 1) and site-specific wind PDFs. Results show the lodging risk range in English stations is 10–17%, in Irish stations is 26–27%, and in Scottish stations is 18–27% stations.

4.2. Lodging Risk in Future Climate Conditions. Based on the data of Table 2, Table 6 illustrates the possible variation in wind speed and rainfall in the future. We will use this range of variations in the analysis of risk that follows.

Using the range of values of rainfall and wind speed calculated above, revised PDFs for these variables can be determined, corresponding to likely future climate conditions. These were calculated by calculating cumulative distribution functions through integrating the PDFs for current conditions, applying the predicted rainfall and wind anomalies to these CDFs and then differentiating them to obtain PDFs relevant to future conditions. Typical values are shown in Figure 9.

Risk calculation for oats was then carried out using the lodging model described in Section 2.2. Using the new wind and rainfall PDFs and averaged agronomic values (Table 4), the failure probability in each anomaly range is obtained. Figure 10 shows the risk contour for Irish conditions, which is similar to what is found for England and Scotland. The figure shows the lodging risk is more affected by changes in the wind speed compared to the rainfall. Thus, if the wind conditions do not change considerably in the future, then the risk of lodging is unlikely to vary significantly from present conditions.

5. Discussion

The above analysis has illustrated that the probability of adverse weather occurrence is a key factor in determining lodging risk. This paper suggests that a double exponential curve can sufficiently represent wind and rainfall PDFs to an acceptable level of accuracy. Although these functions were evaluated for the months of June and July, it is noted that a slight change in the studied period would not significantly alter the obtained PDFs.

Monthly precipitation projections elucidated a dramatic change especially in the second half of the current century, which can reach up to 70%, while monthly average wind speed anomalies were expected to vary by only ±1 m/s. Although such projections are always associated with larger uncertainties in modelling longer periods, it was found that even such a sharp rainfall variation would affect the lodging risk by less than 5%, while 1 m/s reduction/increase in mean hourly wind speed could change the failure risk more than 10%. Thus, demonstrating that in general, the wind speed is the governing parameter for lodging.

The lodging risk was evaluated for the whole range of wind and rainfall variation, with the majority of climate models indicating a decline in the average wind speed in Ireland. Hence, it is reasonable to assume that on average, the risk of oat lodging is likely to reduce. However, the same conclusion cannot be drawn for the UK. Although these conclusions are made based on variations in monthly averages, it is expected that extreme wind events (e.g., storms) will not affect the aforementioned risk assessment as a relation between climate change and summer storminess in the UK which has not been established [33]. Moreover, North Atlantic cyclones are expected to reduce by 10%, the number of extreme storms is projected to be rare, and the majority of such adverse weather conditions is expected to happen in winter [32]; all implying UK and Ireland will not

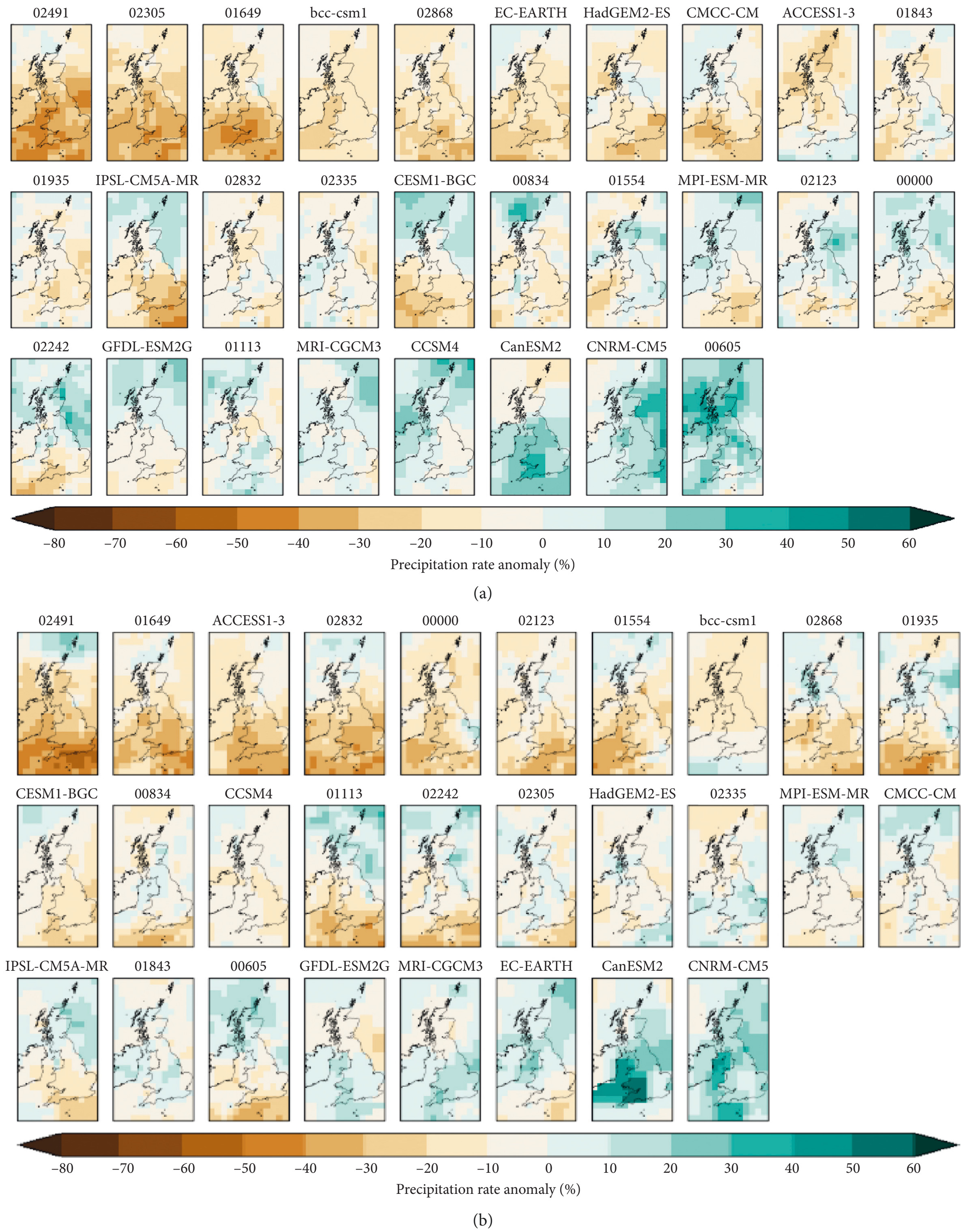


Figure 6: Monthly average precipitation rate anomaly (%) from 2020 to 2049 using baseline 1981–2010 and scenario RCP 8.5 for (a) June and (b) July. (The four-digit number/letters above the projections correspond to the relevant models used for the projections).

face more frequent summer storms in comparison to the current conditions.

This research quantified the oat-lodging risk for the first time based on experimental data obtained from experiments undertaken in Carlow, Ireland. Although the metrological conditions can be described by representative function which were found accurate enough to be used in the British and Irish farmlands, more studies are recommended to investigate if the plant properties change in different sites/years. Moreover, temperature, sunshine,

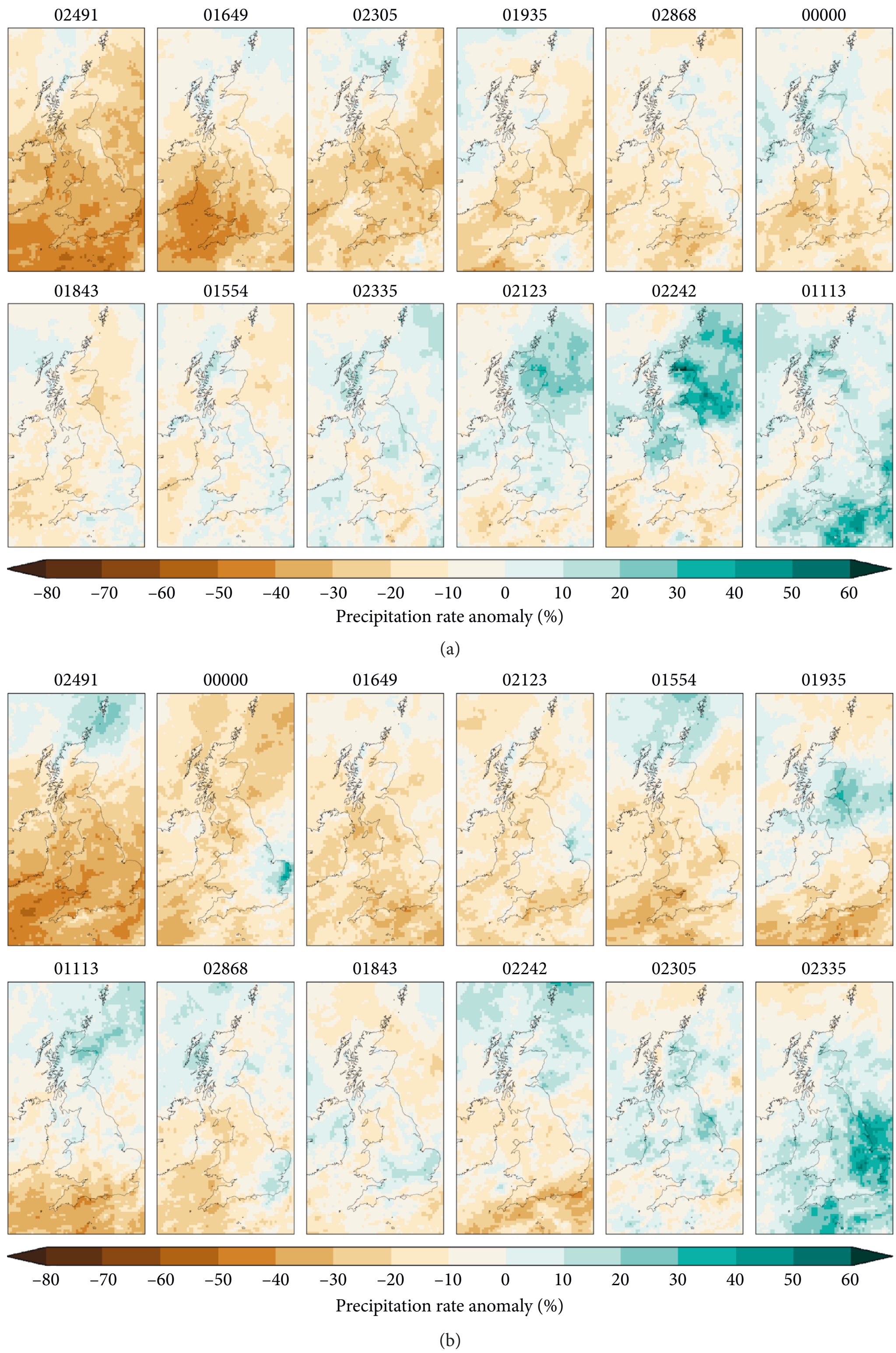
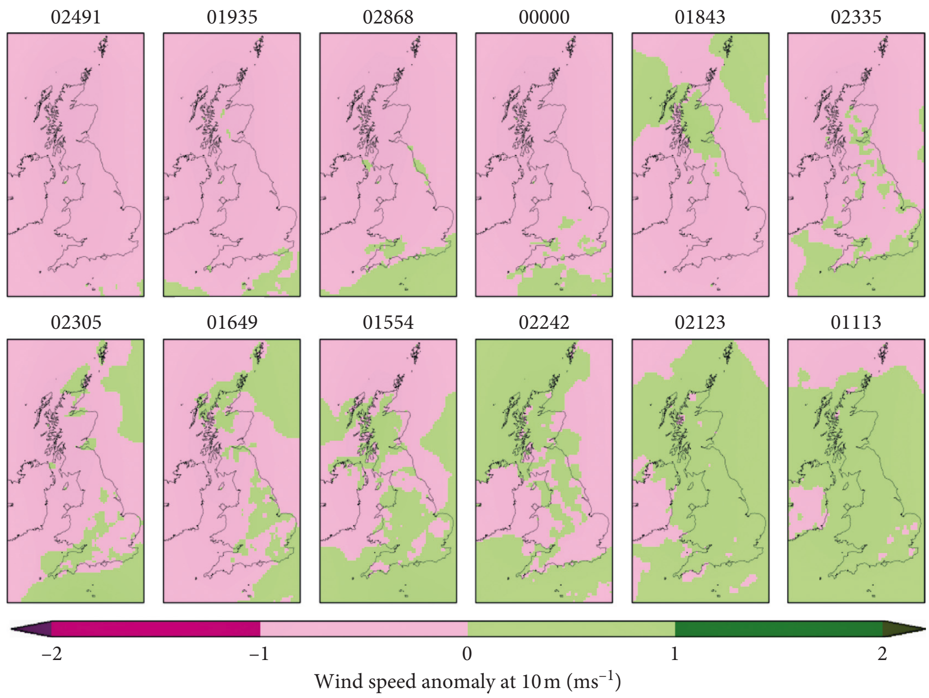
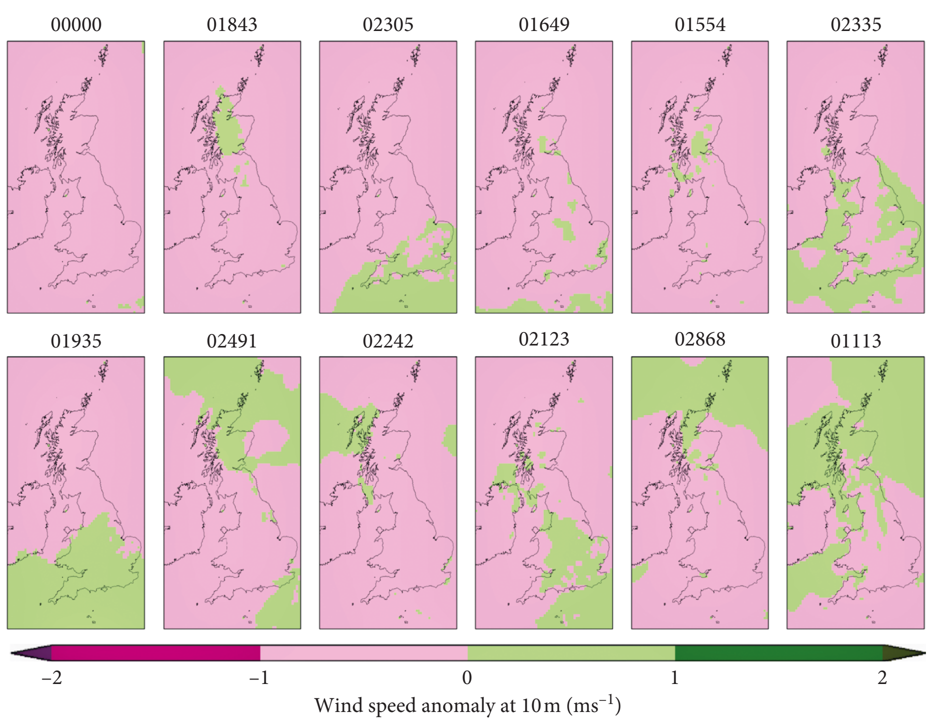


FIGURE 7: Monthly average precipitation rate anomaly (%) in the period from 2020 to 2049 using baseline 1981–2010 and scenario RCP 8.5 for (a) June and (b) July. (The five-digit numbers above each map indicate the PPE model used for the projection).

weather and soil moisture, plant diseases, pest, and other environmental parameters can affect attributes of plants associated with lodging [8, 25]. The natural variation of these parameters and the potential effect of climate change on these factors can also be a point of interest for future research studies.



(a)



(b)

Figure 8: Monthly average wind speed anomaly at 10 m from 2020 to 2049 using baseline 1981–2010 and scenario RCP 8.5 for (a) June and (b) July.

Importantly, from a grower's perspective, this analysis has demonstrated that the effect of climate change on lodging risk is similar to the variation in risk which occurs as a result of plant variations and growing practices—this is an interesting result and enables the potential change in lodging to be appreciated at farm scale.

Table 4: Agronomic, aerodynamic, and soil parameters (letter abbreviation for parameters used can be found in Section 2.2).

Agronomic parameters	Mean	Standard deviation
n	2.02	0.7
a (mm)	3.2	0.6
t (mm)	0.9	0.3
L (m)	1.4	0.3
X (m)	0.64	0.081
d (mm)	58	9.6
l (mm)	91.9	10
Aerodynamic/soil parameters		
ρ (Kg/m^3)	1.2	—
A_{CF} (m^2)	0.016	0.002
θ	0.1	0.04
f_n (Hz)	1.1	0.03
I	0.5	0.16
S (K Pa)	35	5.1

Table 5: Lodging risk variation in different treatments and seed rates.

Variety	Seed rate (m^2)	Risk range (10^{th}–90^{th} percentile)	50^{th} percentile risk
Susceptible	200 seeds	0.06–0.60	0.21
Susceptible	500 seeds	0.11–0.62	0.32
Moderate resistance	200 seeds	0.03–0.46	0.20
Moderate resistance	500 seeds	0.04–0.60	0.26

Table 6: Monthly average wind and rainfall rate anomaly (%) generated by most of the models using baseline 1981–2010 in June and July.

Region	Most likely monthly anomaly to happen			
	2020–2049		2050–2079	
	Rain	Wind	Rain	Wind
South England	−30% to 10%	±1 m/s	−40% to 0%	−1 m/s to 0
West England	−30% to 10%	±1 m/s	−40% to 0%	±1 m/s
Ireland	±20	−1 m/s to 0	−40% to 0%	−1 m/s to 0
Scotland	±20	±1 m/s	−40% to 10%	±1 m/s

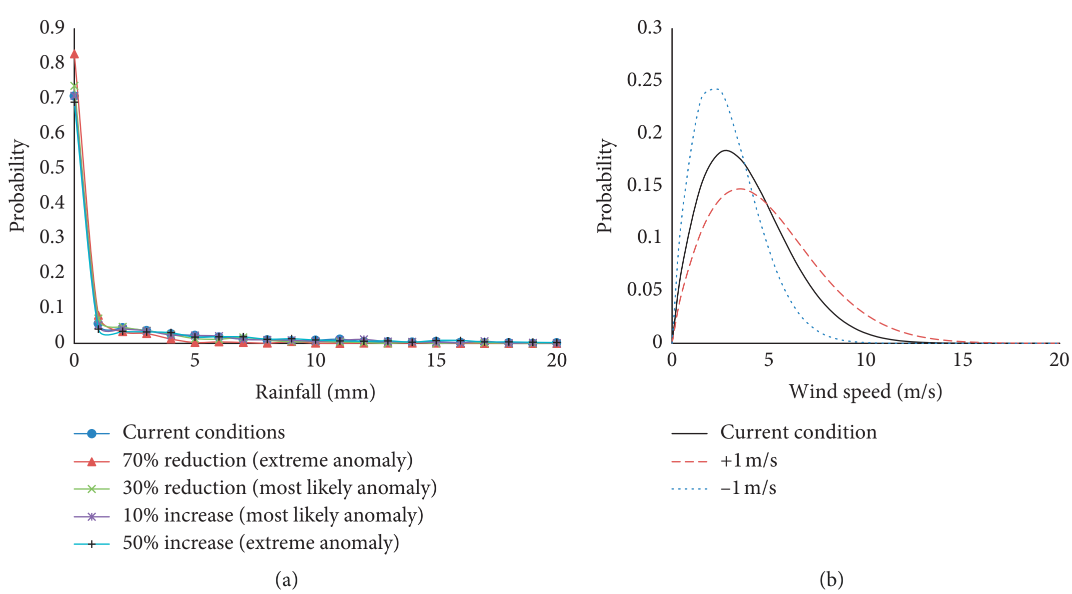


Figure 9: (a) Rainfall and (b) wind PDFs in the current and future climate conditions for Haslemere station (South England).

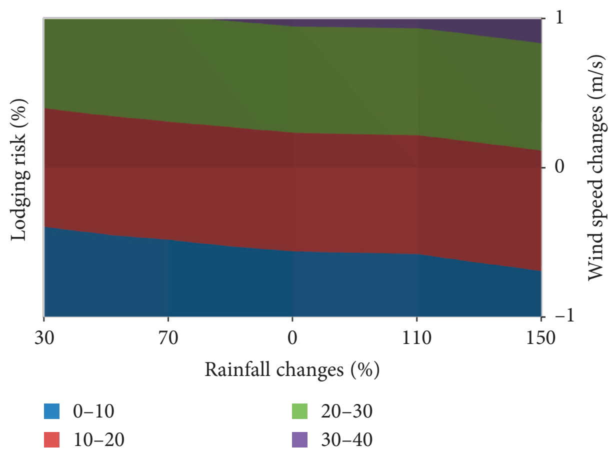


Figure 10: Lodging risk based on wind and rainfall anomalies.

6. Concluding Remarks

This paper has examined the impact that climate change could have on lodging in oats. The following conclusions can be made:

(i) A double exponential PDF can be used to represent rainfall with an acceptable degree of accuracy.

(ii) The risk of oat lodging occurring within a specified period of time (typically June-July) is a complex and nonlinear interaction of wind and rain.

(iii) The predictions of future rainfall are somewhat unclear, with some models suggesting that the rainfall will be less in June and greater in July (and vice-versa). However, in general, it is likely that drier conditions will be experienced in the future during the critical lodging period.

(iv) Similar to rainfall, the predictions of wind speed over the June-July period are model-specific. However, it is likely that if the wind speed changes, the changes will be small (~1 m/s) and as such unlikely to affect lodging.

(v) The analysis undertaken illustrates that lodging is potentially highly susceptible to changes in wind speed and less susceptible to changes in rainfall. Thus, it is tempting to conclude that lodging will reduce in the future (ceteris parbius); however, the uncertainty associated with the wind speed predictions prevents this conclusion from being made with any degree of certainty.

(vi) The impact that climate change may have on oat lodging is consistent with the variation that currently exists through the impact of different husbandry. This is an important point and should provide a degree of comfort to growers.

Data Availability

The historical meteorological data could be downloaded from http://www.met.ie for Ireland and from http://data.ceda.ac.uk for the UK. Additionally, some meteorological data for the UK are provided by Meteorological Office National Meteorological Archive. Requests to access this archive should be made to Meteorological office, enquiries@metoffice.gov.uk. Climate change projection data are available from http://ukclimateprojections.metoffice.gov.uk.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This paper was dedicated to one of the authors, John Finnan, who died in an aircraft accident during the course of the research. John's expertise and input was instrumental for the agricultural elements of the research. However, John also had an uncanny knack of delivering a constructive and well-timed challenge on the meteorological aspects of the research, thereby ensuring that those authors who claim to profess such expertise reflected long and hard on how their message could be delivered more appropriately—something which is key to ensuring successful transdisciplinary research. Perhaps, this is something that we all might like to reflect on as subject boundaries become less opaque—he would have liked that. Thanks are expressed to Walsh Fellowship which funded the first author and to those organisations mentioned in the paper that provided their data free of charge.

References

[1] R. Saboohi, S. Soltani, and M. Khodagholi, "Trend analysis of temperature parameters in Iran," *Theoretical and Applied Climatology*, vol. 109, no. 3-4, pp. 529–547, 2012.

[2] A. Gohari, S. Eslamian, J. Abedi-Koupaei, A. Massah Bavani, D. Wang, and K. Madani, "Climate change impacts on crop production in Iran's Zayandeh-Rud River Basin," *Science of The Total Environment*, vol. 442, pp. 405–419, 2013.

[3] M. E. Brown, B. Hintermann, and N. Higgins, "Markets, climate change, and food security in West Africa," *Environmental Science & Technology*, vol. 43, no. 21, pp. 8016–8020, 2009.

[4] M. Parry, O. Canciani, J. Palutikof, P. Linden, and C. Hanson, *Cliamte Change 2007:Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 2007.

[5] Ethiopian Panel on Climate Change, *First Assessment Report, Working Group II Agriculture and Food Security*, Ethiopian Academy of Sciences, Addis Ababa, Ethiopia, 2015.

[6] J. I. L. Morison and R. B. Matthews, *Agriculture and Forestry Climate Change Impacts Summary Report*, Living With Environmental Change, Swidon, UK, 2016.

[7] T. Hennessy, "The impact of climate change on Irish farming," Teagasc report, Teagasc, Wexford, Ireland, 2010.

[8] P. Berry, M. Sterling, J. Spink et al., "Understanding and reducing lodging in cereals," *Advances in Agronomy*, vol. 84, pp. 215–269, 2004.

[9] M. Sterling, C. Baker, G. Joseph et al., *Mitigating Yield Losses Due to Lodging of Cereal Crops*, International Workshop on

Wind-Related Disasters and Mitigation Tohoku University, Sendai, Japan, 2018.

[10] M. J. Crook and A. R. Ennos, "The mechanics of root lodging in winter wheat, *Triticum aestivum* L.," *Journal of Experimental Botany*, vol. 44, no. 7, pp. 1219–1224, 1993.

[11] P. M. Berry, M. Sterling, C. J. Baker, J. Spink, and D. L. Sparkes, "A calibrated model of wheat lodging compared with field measurements," *Agricultural and Forest Meteorology*, vol. 119, no. 3-4, pp. 167–180, 2003.

[12] C. J. Baker, M. Sterling, and P. Berry, "A generalised model of crop lodging," *Journal of Theoretical Biology*, vol. 363, pp. 1–12, 2014.

[13] J. L. Wright, *Evaluating turbulent transfer aerodynamically within the micro climate of a cornfield*, Ph.D. thesis, Cornell University, Ithaca, NY, USA, 1965.

[14] S. S. Lu and W. W. Willmarth, "Measurements of the structure of the Reynolds stress in a turbulent boundary layer," *Journal of Fluid Mechanics*, vol. 60, no. 3, pp. 481–511, 1973.

[15] M. R. Raupach, J. J. Finnigan, and Y. Brunet, "Coherent eddies and turbulence in vegetation canopies: the mixing layer analogy," *Boundary-Layer Meteorology 25th Anniversary Volume, 1970-1995*, vol. 78, no. 3-4, pp. 351–382, 1996.

[16] J. Finnigan, "Turbulence in plant canopies," *Annual Review of Fluid Mechanics*, vol. 32, no. 1, pp. 519–571, 2000.

[17] C. Py, E. Langre, and B. Moulia, "A frequency lock-in mechanism in the interaction between wind and crop canopies," *Journal of Fluid Mechanics*, vol. 568, pp. 435–449, 2006.

[18] C. J. Baker, "The development of a theoretical model for the windthrow of plants," *Journal of Theoretical Biology*, vol. 175, no. 3, pp. 355–372, 1995.

[19] C. J. Baker, P. M. Berry, J. H. Spink et al., "A method for the assessment of the risk of wheat lodging," *Journal of Theoretical Biology*, vol. 194, no. 4, pp. 587–603, 1998.

[20] M. Sterling, C. J. Baker, P. M. Berry, and A. Wade, "An experimental investigation of the lodging of wheat," *Agricultural and Forest Meteorology*, vol. 119, no. 3-4, pp. 149–165, 2003.

[21] P. M. Berry, M. Sterling, and S. J. Mooney, "Development of a model of lodging for barley," *Journal of Agronomy and Crop Science*, vol. 192, no. 2, pp. 151–158, 2006.

[22] M. Sposaro, P. Berry, M. Sterling, A. Hall, and A. Chimenti, "Development and validation of a model of lodging for sunflower," in *Proceedings of the 17th International Sunflower Conference*, Córdoba, Spain, June 2008.

[23] M. M. Sposaro, P. M. Berry, M. Sterling, A. J. Hall, and C. A. Chimenti, "Modelling root and stem lodging in sunflower," *Field Crops Research*, vol. 119, no. 1, pp. 125–134, 2010.

[24] D. L. Easson, E. M. White, and S. J. Pickles, "The effects of weather, seed rate and cultivar on lodging and yield in winter wheat," *The Journal of Agricultural Science*, vol. 121, no. 2, pp. 145–156, 1993.

[25] P. Berry, J. Spink, R. Sylvester-Braley et al., "Lodging control through variety choice and management," in *Proceedings of the HGCA Conference: Agronomic Intelligence: The Basis for Profitable Production*, Northern Britain, UK, October 2002.

[26] M. Mohammadi, C. Baker, M. Sterling, and J. Finnan, "A study on meteorological parameters in oat lodging," in *Proceedings of the 13th UK Conference on Wind Engineering*, Leeds, UK, September 2018.

[27] P. Martinez-Vazquez, "Crop lodging induced by wind and rain," *Agricultural and Forest Meteorology*, vol. 228-229, pp. 265–275, 2016.

[28] S. Soltani, R. Saboohi, and L. Yaghmaei, "Rainfall and rainy days trend in Iran," *Climatic Change*, vol. 110, no. 1-2, pp. 187–213, 2012.

[29] G. Jenkins, M. Peery, and J. Prior, "The climate of the United Kingdom and recent trends," *UK Climate Projections Report*, Met Office, Hadley Centre, Exeter, UK, 2009.

[30] P. Maisey, F. Fung, G. Harris et al., *UKCP18 Factsheet: Precipitation*, Met Office Hadley Centre, Exeter, UK, 2018.

[31] L. McElwain and J. Sweeney, "Key meteorological indicators of climate change in Ireland," *Environmental Research Centre Report*, Environmental Protection Agency, Wexford, Ireland, 2007.

[32] P. Nolan, "EPA report: ensemble of regional climate model projections for Ireland," *EPA Climate Change Research Report No. 159*, EPA, Wexford, Ireland, 2015.

[33] Meteorological Office, *The United Kingdom's National Weather Service Website*, Met Office, Exeter, UK, 2019.

[34] P. Nolan, J. O'Sullivan, and R. McGrath, "Impacts of climate change on mid twenty first century rainfall in Ireland: a high resolution regional climate model ensemble approach," *International Journal of Climatology*, vol. 37, no. 12, pp. 4347–4363, 2017.

[35] Met Éireann, *National Irish Meteorological Service*, Met Éireann, Dublin, Ireland, 2017, http://www.met.ie.

[36] J. Griffin, *Assessing lodging risk in winter wheat*, Ph.D. thesis, University of Nottingham, Nottingham, UK, 1998.

[37] M. Mohammadi, C. Baker, M. Sterling, and J. Finnan, "Calibration of a model for predicting wind induced failure of oats," in *Proceedings of the International Conference on Wind Engineering (ICWE)*, Beijing, China, February 2019.

[38] New Approaches to Old Problems: Integrating Disciplines to Understand Lodging in Oats, 2018, https://sciencetrends.com/new-approaches-to-old-problems-integrating-disciplines-to-understanding-lodging-in-oats/.

[39] UK research and inovation website, https://gtr.ukri.org/projects.

[40] University of Birmingham website, https://www.birmingham.ac.uk/research/activity/engineering/power-infrastructure/Understanding-reducing-lodging-flattening-maize-and-rice.aspx.

[41] A. G. Chalmers, C. J. Dyer, and R. Sylvester-Bradley, "Effects of nitrogen fertilizer on the grain yield and quality of winter oats," *The Journal of Agricultural Science*, vol. 131, no. 4, pp. 395–407, 1998.

[42] E. M. White, A. S. L. McGarel, and O. Ruddle, "The influence of variety, year, disease control and plant growth regulator application on crop damage, yield and quality of winter oats (*Avena sativa*)," *The Journal of Agricultural Science*, vol. 140, no. 1, pp. 31–42, 2003.

[43] W. Wu and B.-L. Ma, "Erect-leaf posture promotes lodging resistance in oat plants under high plant population," *European Journal of Agronomy*, vol. 103, pp. 175–187, 2019.

[44] R. Clemens and B. J.-W. van Klinken, "Oats, more than just a whole grain: an introduction," *British Journal of Nutrition*, vol. 112, no. S2, pp. S1–S3, 2014.

[45] F. Thies, L. F. Masson, P. Boffetta, and P. Kris-Etherton, "Oats and CVD risk markers: a systematic literature review," *British Journal of Nutrition*, vol. 112, no. S2, pp. S19–S30, 2014.

[46] P. M. Ryan, L. E. London, T. C. Bjorndahl et al., "Microbiome and metabolome modifying effects of several cardiovascular disease interventions in apo-E−/− mice," *Microbiome*, vol. 5, no. 1, p. 30, 2017.

[47] G. Gillespie, L. Brennan, J. Burke, and D. Forristal, "Oats: food and crop products CROPQUEST," 2016, https://www.teagasc.ie/media/website/crops/crops/Oats-food-and-Crop_products.pdf.

[48] National Statistics, *Farming Statistics Provisional Crop Areas, Yields and Livestock Populations*, National Statistics, London, UK, 2018, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/747210/structure-jun2018prov-UK-11oct18.pdf.

[49] CEDA (Centre for Environmental data Analysis) Archive, 2016, http://data.ceda.ac.uk.

[50] Tillage Sector Development Plan, *Teagasc Tillage Crop Stakeholder Consultative Group*, Tillage Sector Development Plan, Dublin, Ireland, 2012.

[51] J. Holmes, *Wind Loading of Structures*, Taylor & Francis, New York, NY, USA, 2nd edition, 2007.

[52] G. Joseph, C. Baker, M. Sterling, S. Gillmeier, and D. Soper, "Calibration of a generalized crop lodging model for maize and oilseed rape," in *Proceedings of the 13th UK Conference on Wind Engineering*, Leeds, UK, September 2018.

[53] P. M. Berry, J. M. Griffin, R. Sylvester-Bradley et al., "Controlling plant form through husbandry to minimise lodging in wheat," *Field Crops Research*, vol. 67, no. 1, pp. 59–81, 2000.

[54] UK Climate Projections Website, 2018, http://ukclimateprojections.metoffice.gov.uk.

[55] The Intergovernmental Panel on Climate Change's Latest 5th Assessment Report, 2018, http://www.ipcc.ch.

[56] F. Fung, P. Bett, P. Maisey et al., *UKCP18 Factsheet: Wind*, Met Office Hadley Centre, Exeter, UK, 2018.

[57] J. M. Murphy, G. R. Harris, D. M. H. Sexton et al., *UKCP18 Land Projections: Science Report*, Met Office Hadley Centre, Exeter, UK, 2018.